

LETTER

Catastrophic bleaching in protected reefs of the Southern Great Barrier Reef

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Scientific Significance Statement

Ocean heating is causing mass coral bleaching, raising concern for a vast diversity of species that depend on coral reefs to exist and for the significant services coral reefs provide to humanity including food security and shoreline protection. The 2023–2024 global marine heatwave was extreme in triggering coral bleaching and high mortality. The drivers of coral death, rapid demise by heating or slow decline due to starvation by bleaching are a challenge to discern. Coral mortality data are scarce, particularly with respect to taxonomic detail. Our observations on initial responses to an intense marine heatwave show rapid bleaching, disease onset and mortality in diverse corals including genera that are considered resilient. This information is essential to predict how the species composition of coral reef ecosystems will change in a warming world.

Abstract

The iconic Great Barrier Reef (GBR) experienced mass coral bleaching in early 2024. In the southern GBR, heat stress triggered severe and widespread bleaching to levels not previously recorded and impacted a diverse range of coral genera at One Tree Reef (OTR). Over 161 d, we tracked the health of 462 coral colonies from heatwave peak to autumn and winter cooling. In February and April, 66% and 80% of the colonies were bleached, respectively. By May, 44% of the bleached colonies were dead and 53% in July. In July, 31% of colonies were still bleached and 16% recovered. *Goniopora* developed black band disease contributing to high mortality. Colony collapse occurred in *Acropora* (95% mortality) with accumulation of algal-fouled fragments. In-water tracking of individual colonies showed rapid bleaching, disease onset and mortality. The protected status and offshore location did not protect OTR from heat stress bleaching and mortality.

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The crucial ecosystem services that tropical reefs provide as habitat for a vast biodiversity and in providing food security, revenue, and shoreline protection for humanity depend on the integrity of corals, the core foundational organisms. In a rapidly heating ocean, coral reefs are in peril, succumbing to mass bleaching and mortality. The fourth global coral bleaching event started in the Caribbean and was followed by bleaching on the Great Barrier Reef (GBR) (National Oceanic and Atmospheric Administration [NOAA], 2024). The highest temperatures for centuries wrought severe impacts across the GBR (Cantin, James, and Stella 2024; Henley et al. 2024).

Mass bleaching along the GBR started in early 2024 following heat build-up in December (Cantin, James, and Stella 2024). Aerial surveys revealed severe bleaching levels (> 90% bleached corals) widespread across regions (north, central, south), the first such event to have this impact (Cantin, James, and Stella 2024). This is the seventh mass bleaching event on the GBR since 1998 and the fifth since 2016 (Hughes et al. 2021; Cantin, James, and Stella 2024).

Coral bleaching is a heat-induced stress response where the relationship between corals and their endosymbiotic dinoflagellates breaks down. This causes loss in coral color and the nutrients provided by the endosymbionts leading to coral starvation and mortality if their symbionts do not return. The outcomes of bleaching depend on the level of temperature stress, how long the stress lasts and coral species (Hughes et al. 2018). Mortality from bleaching is typically associated with slow starvation and eventual death which can take weeks to months. Intense heating can cause abrupt mortality irrespective of bleaching status (Hughes et al. 2018; Hoegh-Guldberg et al. 2023).

Mass bleaching of corals can be inferred from the satellite-based metric degree heating weeks (DHW, °C weeks), the global bleaching alert product of the NOAA (Skirving et al. 2020). More directly, bleaching on the GBR has been quantified at large spatial scales by aerial surveys (Hughes et al. 2017). On a finer scale, bleaching has been quantified through monitoring at the coral colony level (Baird and Marshall 2002).

Given record-breaking ocean heating in 2023, the outlook for the GBR in the 2024 austral summer was of concern (Hoegh-Guldberg et al. 2023). For the first time in decades, bleaching was severe in the southern GBR (> 90% score, Cantin, James, and Stella 2024). During the 2016 heatwave, this region started to bleach but was spared by cooling from a cyclone (Hughes et al. 2017). The southern GBR bleached in 2020 (Hughes et al. 2021) but did not reach the DHW values at which mortality would be expected (AIMS 2021) and it appears that coral mortality was low (Briggs et al. 2024).

The onset of coral bleaching at One Tree Island and Heron Island reefs, southern GBR was observed in January and February 2024. We instigated a monitoring program at One Tree Reef (OTR) to follow the fate of coral colonies to determine if this event would expand with respect to the extent of coral genera and colonies impacted. Our study involved in-water monitoring of individual colonies to quantify genus level mortality. Coral mortality data are scarce, particularly with respect to community wide taxonomic detail. We tracked the health of 462 coral colonies from the peak of summer heat stress through autumn and winter cooling over 161 d. Our aim was to quantify initial responses to identify the corals that died quickly due to heat stress, those that bleached and

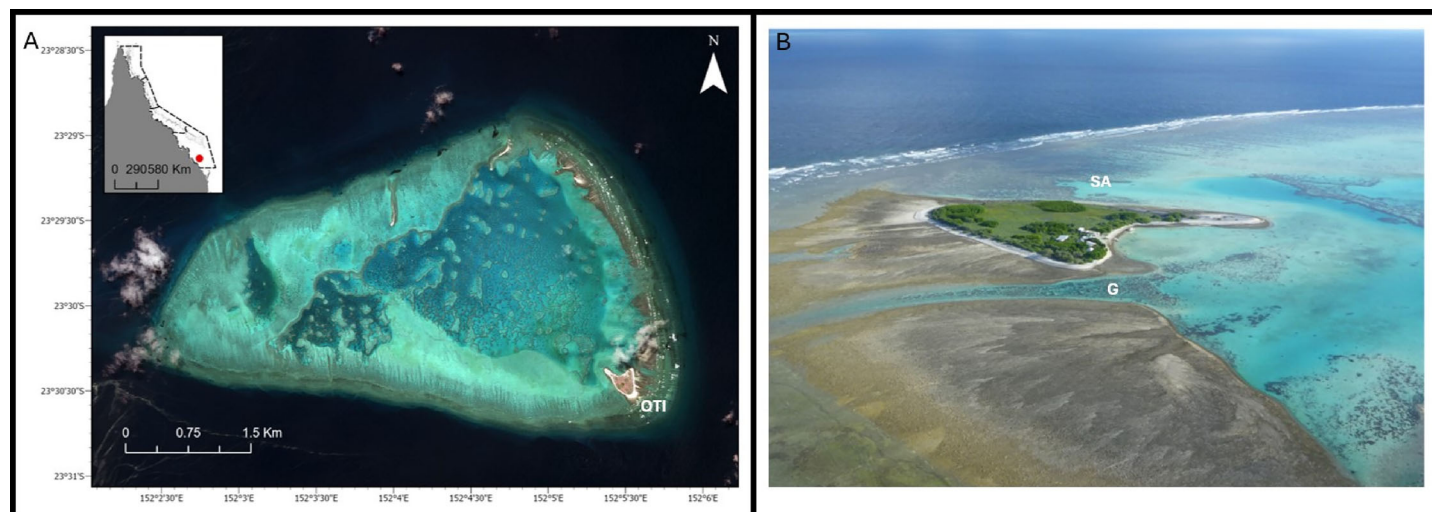


Fig. 1. Location of One Tree Island in the southern Great Barrier Reef. **(A)** Map of northern Queensland with the red dot on insert showing the location of One Tree Island (OTI). **(B)** The locations where tracking of individual coral colonies was done, the Gutter (G) and Shark Alley (SA) are located adjacent to One Tree Island.

died over time, corals that recovered and those that did not bleach. Using long-term in situ temperature data from the OTR site we determined the DHW that induced bleaching and optimized this metric following Whitaker and DeCarlo (2024) to quantify the heat stress accumulation experienced by the corals. We also calculated the satellite-based DHW following the NOAA metric.

Methods

Location and colony monitoring

One Tree Reef (23.51°S, 152.09°E) is a platform reef located 100 km offshore in the Capricorn Bunker Group, southern GBR (Fig. 1A). This reef has been protected from extractive activities and tourism for 50 years under the GBR Marine Park zoning plan as a Scientific Zone with limited access. With its distance from the mainland, it is protected from coastal pollution and development. We monitored individual coral colonies at two sites in the lagoon (2 m depth), the Gutter, a shallow channel that connects to the open ocean and at Shark Alley, a shallow bay that also connects to the open ocean (Fig. 1B). Over 161 d we followed individual colonies, from the extreme heatwave to autumnal cooling, February to May (74 d) to quantify early mortality and how this differed across genera and in July (mid-winter) to quantify later mortality/recovery.

To ensure that we could identify individual coral colonies over time, we placed markers and numbered tags on the benthos to guide the surveys. Videos taken along the survey route facilitated colony identification. On each survey event photographs (1000+) were taken at a range of distances from the colonies including images with the Coral Watch coral health chart. With this information, we identified 462 colonies (bleached/not bleached) in February 2024 that could be tracked in repeated health assessments (July, $n = 459$, we could not locate three colonies) (Byrne et al. 2024). The colonies were rephotographed after 40 (April), 74 (May), and 161 (July) days. We noted if other symbiotic organisms bleached (e.g., anemones).

At each time, colonies were categorized as bleached (pale, fluorescent, white) or dead (90–100% dead with algal fouling). Recovered colonies were 90–100% back to normal color as indicated by the Coral Watch chart. Colony collapse indicated detachment of the dead skeleton from the reef which accumulated as algal fouled rubble fragments on the benthos or disappeared between visits.

Heat exposure and duration

Temperature data from the study site were available from in situ sensors (HOBO loggers $\pm 0.5^\circ\text{C}$, frequency 30 min) that have been deployed where the coral colonies were surveyed for 20 yr (see Supporting Information Table S1). The maximum monthly mean (MMM) was obtained from the monthly mean temperature in 12 calendar months, and the hottest month was March (mean = 27.59°C , $n = 11$ yr; Supporting

Information Table S1). March data were used to determine the climatological baseline maximum monthly mean to quantify heat stress accumulation (intensity and duration) at the level of the corals using the DHW metric (method: <https://coralreefwatch.noaa.gov/satellite/methodology/methodology.php>). This model uses the cumulative sea surface temperature (SST) summed over 12 weeks (84 d) in context with historic maximum mean temperature to calculate the intensity of heating and bleaching risk. The model indicates that 4 DHW above the historic mean prompts bleaching while 8 DHW drives mortality (Skirving et al. 2020).

Using the in situ data we applied threshold modifications (0.4°C warming cut-off, 11 weeks accumulation, 3 DHW, Whitaker and DeCarlo 2024) as potentially more representative of bleaching severity (Fig. 2A). DHW based on satellite data from daily global 5 km sea surface temperature (CoralTemp version 3.1) was also determined as this is the basis of NOAA's bleaching index (Fig. 2B). Deeper water (20 and 30 m) temperature data were obtained from monitoring stations on north and east sides of the reef (<https://spotters.sofarocan.com/?spotter-filter=SPOT-30855C>; <https://spotters.sofarocan.com/?spotter-filter=SPOT-30856C>).

Data analysis

Photographs of the 462 coral colonies were used to identify the colonies that bleached in February ($n = 305$) and April ($n = 370$) summarized at the genus level (Supporting Information Table S2). The fate of these corals was determined in May and July. To show the trajectory of mortality, Kaplan–Meier Survival probability curves (Pocock, Clayton, and Altman 2002) were constructed for genera where we tracked 20+ colonies using the survival package (Therneau 2020) and survminer package in R (ver 0.4) (Kassambara et al. 2021). Mortality data at the two sites at the end of the study in July for the five most abundant genera (*Acropora*, *Isopora*, *Goniopora*, *Pocillopora*, and *Porites*) were analyzed using Fisher's exact test.

Results and discussion

With extreme heating regimes emerging on coral reefs globally, we need better mortality estimates with respect to timing, rapid death or slower bleaching/starvation death, and in context with on reef conditions. The weeks following the onset of bleaching are critical in determining the fate of corals, the pace of health decline and the species that survive or perish (Hughes et al. 2018; Hoegh-Guldberg et al. 2023). Given the differences in the vulnerability of coral genera to bleaching and differences in thermal tolerance and recovery potential, in-water monitoring of individual colonies as undertaken here provides insight as to the heat stress response with respect to coral diversity (Hughes et al. 2018).

The corals paled through January and by early February bleaching was underway in many genera (Figs. 3, 4), including in corals (e.g., *Porites*) considered to be thermally resilient.

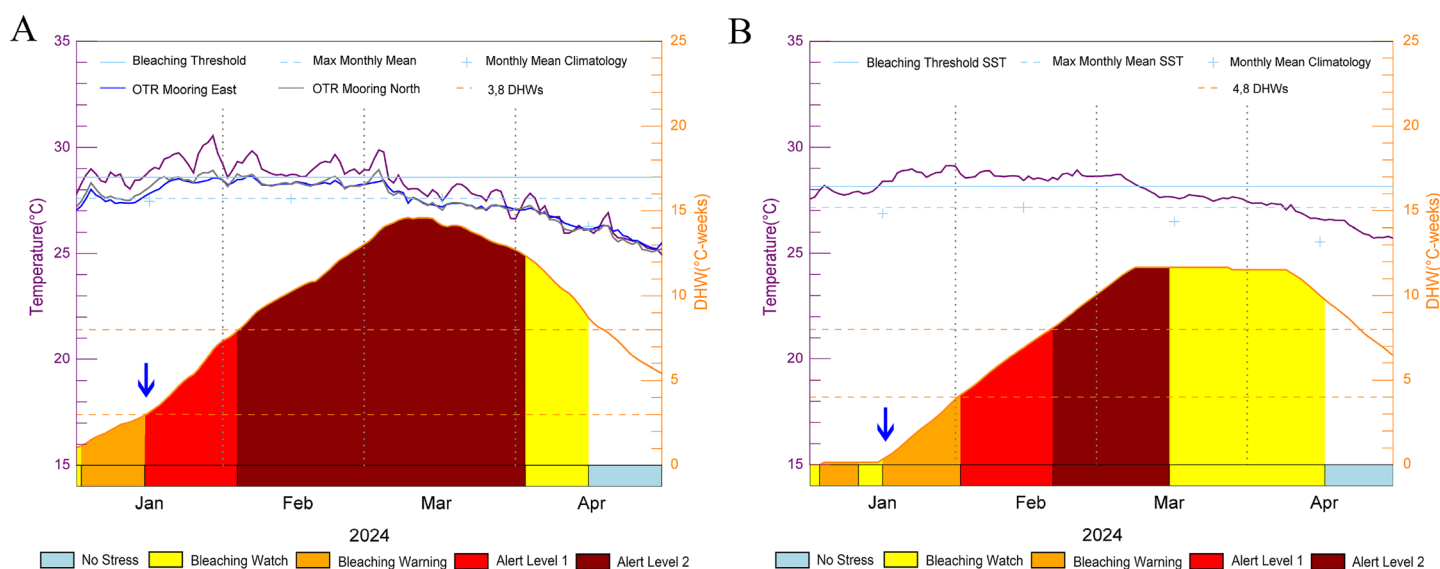


Fig. 2. (A) Heatwave conditions recorded January to March with cooling in April at One Tree Reef in 2024 determined from in situ logger data showing degree heating week (DHW) and bleaching alert levels. The DHW was determined using the threshold modifications (0.4°C warming cut-off, 11 weeks accumulation, 3 DHW) suggested by Whitaker and DeCarlo (2024). The purple line shows the mean daily temperature. The gray and blue lines are from the north and east off reef logging stations (see “Methods” section), respectively. (B) Degree heating week determined from satellite-derived SST using the NOAA metric. In both figures, the colored rectangles below the line represent the maximum NOAA bleaching alert level within 7 d. The arrow shows when corals started to pale in mid-January indicating the onset of bleaching.

Other zooxanthellate species (anemones) also bleached (Supporting Information Fig. S1). The severe conditions and rapid coral health decline had not been previously seen in this region.

Degree heating week conditions

While the DHW model of bleaching alert is important for predicting bleaching events, the satellite-based approach has limitations with respect to predicting the bleaching severity and cannot discern fine scale and regional variation in the coral stress response (Hughes et al. 2018; Whitaker and DeCarlo 2024). Based on in situ logger data and application of threshold modifications (0.4°C warming cut-off, 11 weeks accumulation, 3 DHW), our study site reached Alert Level 1 (4 DHW) on 16 January and quickly entered Alert Level 2 (8 DHW) on 4 February (Fig. 2A). Level 1 is 8 d and Level 2 is 4 d earlier than that determined using the NOAA metric (1.0°C cut-off, 12 weeks, 4 DHW) (Fig. 2B) and reflects on-reef conditions as extensive bleaching was evident in late January and early February. Accumulated heat peaked at 14.607°C-weeks on 9 March. The bleaching alert level remained high through the end of March (Fig. 2).

The peak daily mean temperature measured by the loggers near the surveyed corals was 30.55°C on 29 January, while the satellite sea surface temperature peaked at 29.13°C on 30 January. On-reef sensor temperatures were higher compared to satellite sea surface temperatures showing the importance of habitat level data to capture thermal stress levels.

Accurately understanding the thermal stress conditions is essential for informing climate models related to predicting the severity of and extent of bleaching. Deep water adjacent to the reef (20 and 30 m) had average temperatures > 27.5°C with maximal bottom temperatures reaching 28.99°C (east) and 29.17°C (north) (see “Methods” section).

Fate of individual coral colonies

In February and April 66% ($n = 305$) and 80% ($n = 370$) of the 462 tracked coral colonies were bleached, respectively (Figs. 3–5). Bleaching among taxa and outcomes over time are detailed in Supporting Information Tables S2–S4. For the corals that bleached in February, 47% were dead in May with their surface covered by algae. For all corals that bleached by April, 44% and 52% were dead in May and July, respectively. By May and July, 12% and 16% of bleached colonies had recovered, respectively (Supporting Information Table S3). For *Acropora*, *Echinopora*, *Favites*, *Isopora*, *Montipora*, *Platygyra*, *Pocillopora*, and *Seriatopora*, 100% of the colonies bleached. *Goniastrea* and *Pavona* were less sensitive (47% and 10% bleached, respectively). *Porites* also bleached (69% of colonies).

Acropora had the highest mortality 92% and 95% dead ($n = 37$ colonies) by days 40 and 161, respectively (Fig. 3D; Supporting Information Table S2). Mortality by July was also extensive for *Isopora* and *Goniopora* colonies (63% and 73%, respectively) and was lowest in *Porites* (31%, $n = 129$ colonies) and *Pocillopora* (23%, $n = 22$ colonies) (Fig. 5). These latter

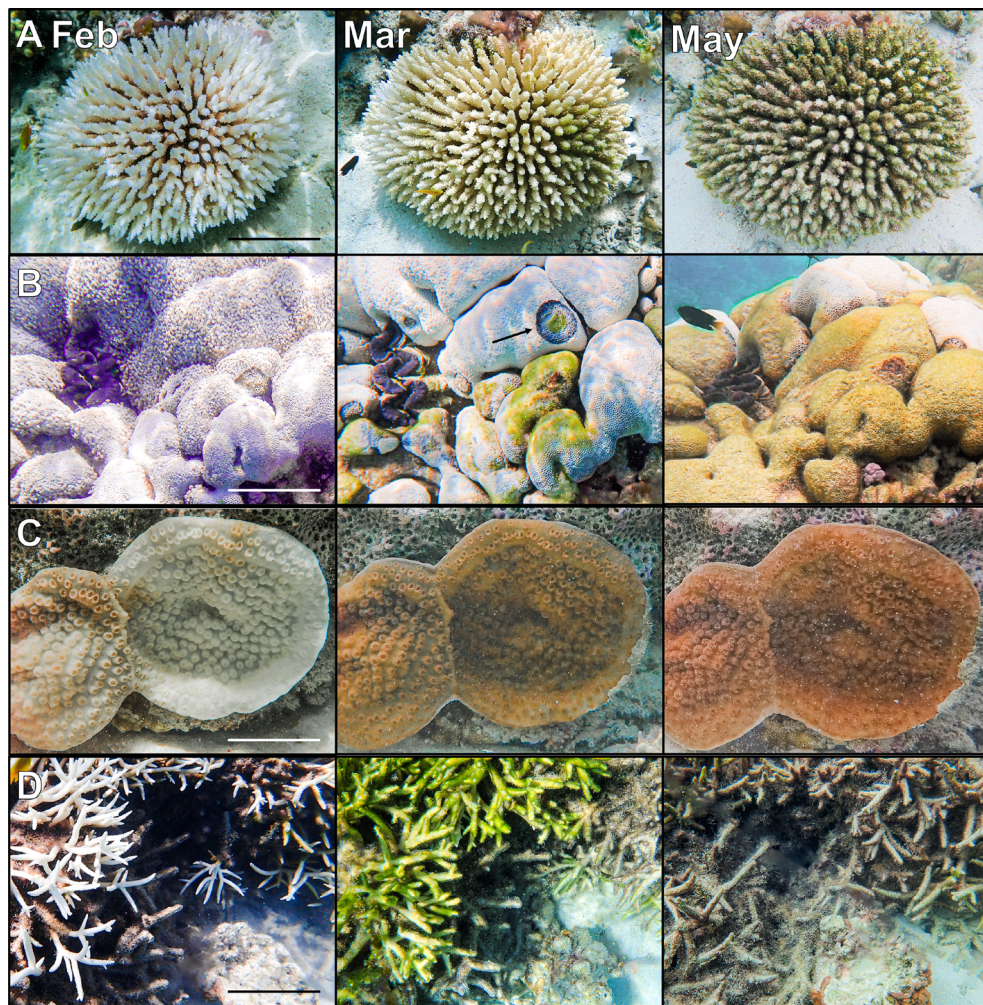


Fig. 3. Images of individual coral colonies monitored for health assessment in February, March, and May 2024. **(A)** *Acropora* colony bleached in February, covered in algae in March and May. **(B)** *Goniopora* colony starting to pale in February, with black band disease (arrow) in March and mostly dead in May. The *Tridachna* clam facilitates orientation. **(C)** *Echinopora* colony started to bleach in February followed by recovery. **(D)** *Acropora* colony, bleached in February, dead in March covered by algae and by May was collapsing into rubble. Scales: **(A)** 130 mm, **(B)** 160 mm, **(C)** 43 mm, and **(D)** 185 mm.

genera exhibited recovery in May and July (Fig. 5A; Supporting Information Table S2).

The *Goniopora* that bleached became infected by black band disease (BBD) along the edge of the bleached tissue. This disease was detected after the first signs of bleaching but may have gone undetected before the black bands become prominent. Black band disease caused polyp necrosis and death as the band invaded and reduced live tissue cover (Figs. 3B, 4). By May, 63% of the colonies ($n = 112$ colonies) were infected (Fig. 4). In total, 95% of the *Goniopora* bleached and of these, 66% developed black band disease. This likely contributed to high mortality (May, 54%; July, 73%) of *Goniopora* colonies (Fig. 5). Heat stress and bleaching are linked to coral disease (Brodnicke et al. 2019), but our surveys indicated that black band disease was only present in *Goniopora*.

Overall, the fate of many colonies with respect to mortality was clear by May, except for the *Goniopora* colonies many

of which died between the May and July surveys (Fig. 5). There were clear differences with respect to resistant and sensitive genera. Mortality of *Acropora*, *Isopora*, and *Goniopora* occurred quickly (Fig. 5B). Virtually all *Acropora* and *Goniopora* colonies alive in May were still bleached, and most of these were dead by July (Fig. 5). The mortality observed for these genera contrasts, with that for the more resilient corals. Most *Pavona* (90%, $n = 20$ colonies) did not bleach and many *Porites* (31%, $n = 186$ colonies) and *Goniastrea* (53%, $n = 19$ colonies) did not bleach (Supporting Information Table S2). Identification of the colonies that had recovered from bleaching by July (e.g., *Porites* 26% recovered; *Pocillopora* 27% recovered) is also key to understanding how reef composition may change. There was no difference in mortality of *Acropora*, *Isopora*, *Goniopora*, and *Pocillopora* colonies at the two sites, except for *Porites* which had lower mortality in Shark Alley ($p = 0.0073$).

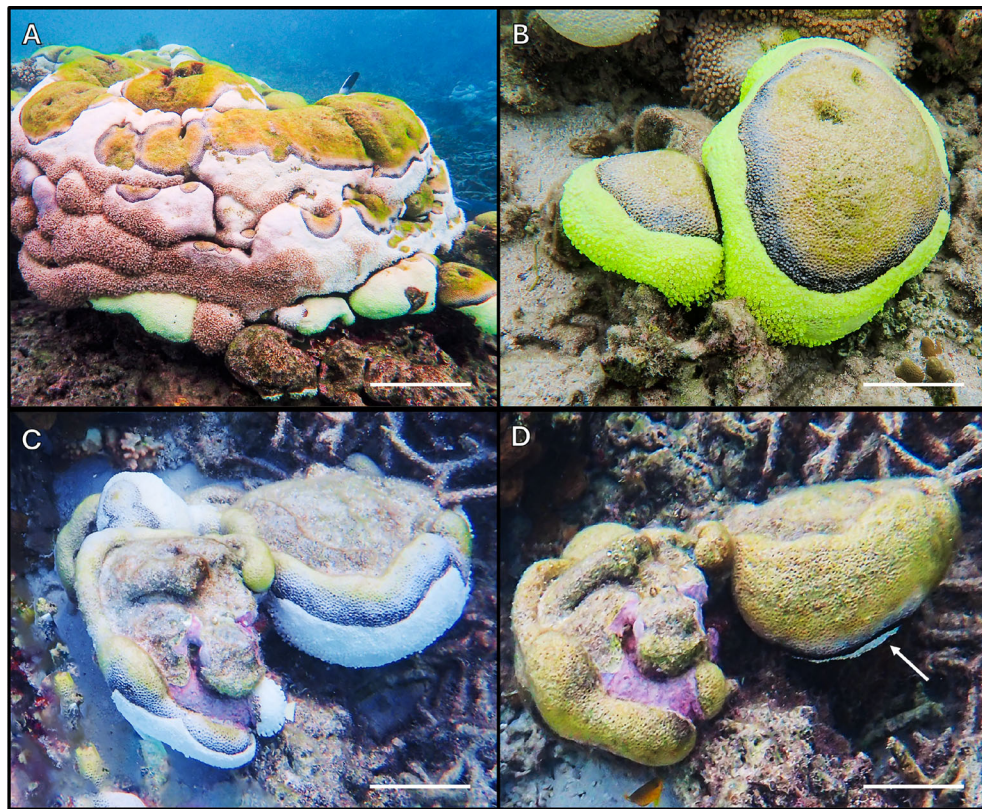


Fig. 4. Black band disease in *Goniopora*. (A) The bleached top region of the colony has the disease while the lower portion has normal color with some green, fluorescent bleaching patches. (B) Fluorescent green polyps in a diseased colony. (C, D) A bleached colony photographed in March (C) with black band disease. (D) The disease has progressed such that only a small patch of live bleached polyps (arrow) is present in May. Scales: (A) 50 cm and (B–D) 10 cm.

From reef to rubble

Acropora and *Seriatopora* had 95% and 100% colony mortality, respectively. As the branches broke off, they formed piles of algal covered fragments/rubble on the benthos and some large dead portions of *Acropora* detached from the colony and were no longer in view (Fig. 3D; Supporting Information Table S3). This indicated the start of colony structure collapse and that generation of rubble from dead coral skeleton was rapid.

As the frequency of coral bleaching outstrips the ability of reefs to recover, tropical ecosystems are transitioning to new configurations of species and seascape topology (Hughes et al. 2018; Stuart-Smith et al. 2018). The fate of the skeleton of dead coral colonies differs between species and habitats (Morais et al. 2022; Kopecky et al. 2024). We have a poor understanding of the fate of dead coral skeleton, the timing of colony collapse and eventual erosion of the skeleton. What this means for the reef framework and subsequent recruitment and recovery especially when large portions of the reef undergo mortality is also unclear (Kopecky et al. 2024).

It is important to determine how long the dead reef framework remains as it succumbs to physical and bioerosive forces.

These changes have marked ecological outcomes due to reduction in habitat structural complexity upon which many species depend and the difference in coral recruitment to pavement substratum and coral rubble (Kopecky et al. 2024). It can take months to years for coral skeletons to erode, standing in place or as collapsed rubble, depending on species and locations (Hutchings, Peyrot-Clausade, and Stuken 2013; Morais et al. 2022). These dynamics are important as heatwave mortality is becoming more frequent and reefs are increasingly becoming dominated by coral rubble (Wolfe, Kenyon, and Mumby 2021; Kenyon et al. 2023). Our tracking of individual coral colonies from the outset of bleaching to identify those that died showed that the transition from reef to rubble can occur quickly.

Management implications

Our repeated assessment of individual coral colonies through a major bleaching event compliments broad scale aerial surveys undertaken by management, which are largely based on coral cover (Cantin, James, and Stella 2024; see also Hughes et al. 2017) in providing a nuanced record with respect to on-reef changes. While this study focused

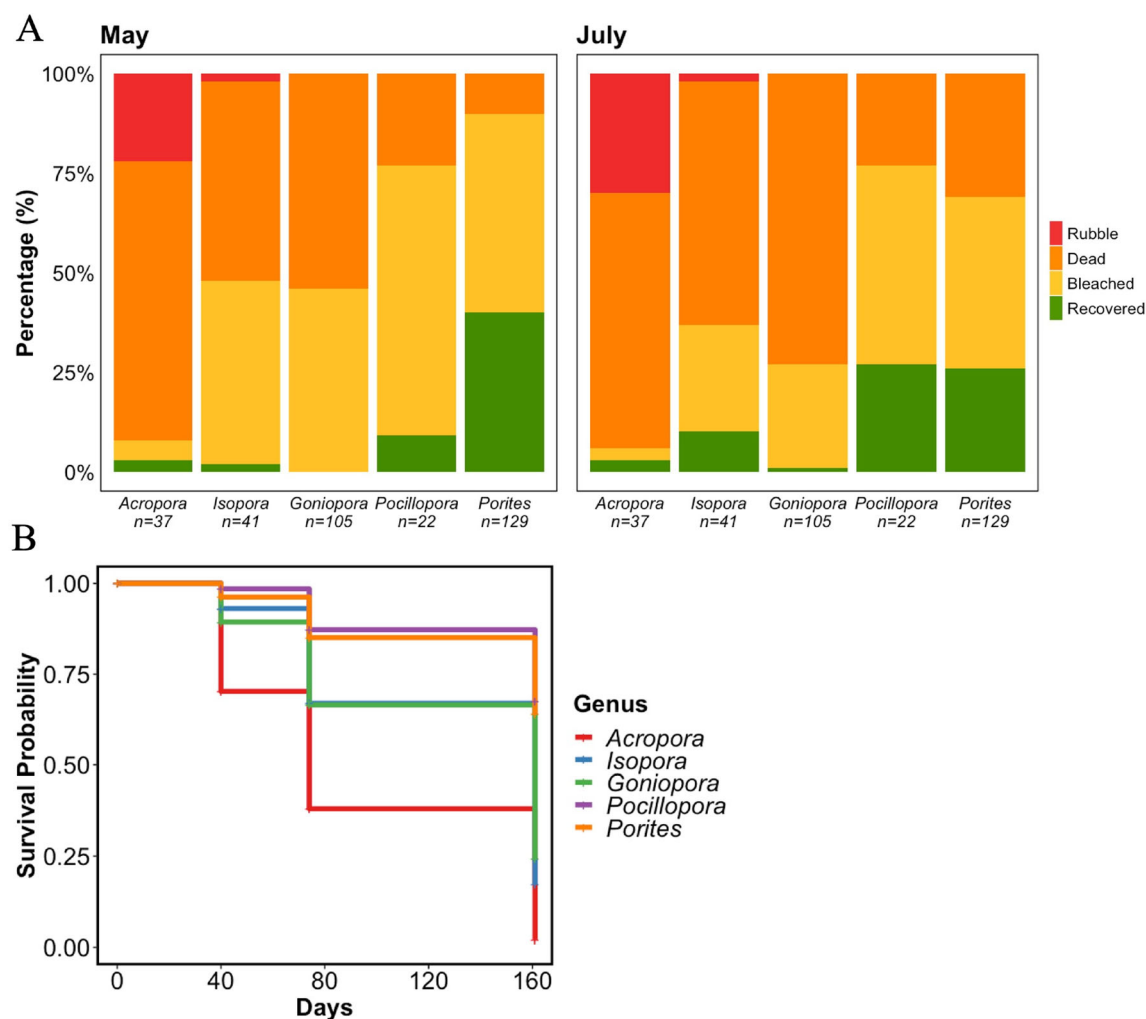


Fig. 5. Fate of individual coral colonies from the onset of bleaching in February to autumn cooling and mid-winter. **(A)** The response of colonies from five genera that were bleached in February and/or April in May and July. **(B)** Kaplan–Meier survival probabilities of bleached colonies of *Acropora* ($n = 37$), *Isopora* ($n = 41$), *Goniopora* ($n = 105$), *Pocillopora* ($n = 22$), and *Porites* ($n = 129$).

on two back reef lagoon sites in the southern GBR, our results reflect GBR-wide trends for the 2024 event (Cantin, James, and Stella 2024) and emerging data indicating impacts at broader spatial scales (Sommer, pers. comm.). Information on the response of coral colonies faced with heat stress and how this varies between genera is important in predicting how tropical reef systems are changing at the species and community level. For management, these data provide crucial insights for predicting changes in the foundational structures of coral reefs, upon which a great diversity of species depends on for survival.

Changes in reef communities following the 2024 mass bleaching will become apparent over coming months. Our monitoring from the outset of bleaching provides the evidence to link those changes with causative stress. While protection from anthropogenic disturbances can enhance

prospects for coral survival through heatwaves (Donovan et al. 2021), the protected status and offshore location did not guard OTR from mass coral bleaching and mortality. The clear link between the onset of bleaching and fate of individual colonies with in situ temperature data allows for a true understanding of the heat stress level dividing the winners and losers.

As corals can recover from mild bleaching when water cools, there is a perception that while bleaching is bad, it is not necessarily catastrophic. What we observed at OTR was by contrast, catastrophic. Rapid high mortality was observed, leaving no opportunity for these corals to recover. Due to the severe heatwave many of the corals were dead within 40–70 d. The skeletons of *Acropora* quickly fouled with algae and some colonies started to fragment and transition to rubble. These new coral fragments will contribute to sedimentary environments

in island dynamics and reef flats (Fellows et al. 2024). The reef to rubble phenomenon is a major driver of transformation to new tropical ecosystem states that are difficult to recover from and needs urgent attention (Kenyon et al. 2023).

Mass coral bleaching is a global phenomenon and on the GBR, its frequency has increased such that it is becoming a biennial event. Coral reefs, provide crucial ecosystem services, making their responses to ocean heating a matter of great concern worldwide. With respect to coral reef futures, we no longer have the tragedy of the distant horizon, where catastrophic conditions and ecosystem changes seem far into the future and so action is delayed. Our findings for corals faced with the 2024 extreme heatwave reinforces the need for urgent global action now to adhere to ambitious climate and reduced emissions targets.

Author Contributions

Maria Byrne led the manuscript and designed the study. Alexander Waller, Claire E. Raymond, Kate Whitton, Matthew Clements, Aisling S. Kelly, and Claire E. Raymond conducted surveys. Alexander Waller conducted data analyses. Bailu Liu and Shawna A. Foo analyzed temperature data. Michael J. Kingsford and Ana Vila-Concejo provided temperature data. Monique Webb assisted with figs. Maria Byrne wrote the paper, and all authors approved the final submission.

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

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